

TECHNICAL REPORT ARCCB-TR-02006

**YIELD PRESSURE MEASUREMENTS AND  
ANALYSIS FOR AUTOFRETTAGED CANNONS**

**JOHN H. UNDERWOOD  
DAVID B. MOAK  
MICHAEL A. AUDINO  
ANTHONY P. PARKER**

**MAY 2002**



**US ARMY ARMAMENT RESEARCH,  
DEVELOPMENT AND ENGINEERING CENTER  
CLOSE COMBAT ARMAMENTS CENTER  
BENÉT LABORATORIES  
WATERVLIET, N.Y. 12189-4050**



**APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED**

**20020529 098**

## **DISCLAIMER**

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

The use of trade name(s) and/or manufacturer(s) does not constitute an official endorsement or approval.

## **DESTRUCTION NOTICE**

For classified documents, follow the procedures in DoD 5200.22-M, Industrial Security Manual, Section II-19, or DoD 5200.1-R, Information Security Program Regulation, Chapter IX.

For unclassified, limited documents, destroy by any method that will prevent disclosure of contents or reconstruction of the document.

For unclassified, unlimited documents, destroy when the report is no longer needed. Do not return it to the originator.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE May 2002	3. REPORT TYPE AND DATES COVERED Final		
4. TITLE AND SUBTITLE YIELD PRESSURE MEASUREMENTS AND ANALYSIS FOR AUTOFRETTAGED CANNONS		5. FUNDING NUMBERS AMCMS No. 6226.24.H180.0 PRON No. TU1E1F261ABJ		
6. AUTHORS John H. Underwood, David B. Moak, Michael A. Audino, and Anthony P. Parker (Royal Military College of Science, Cranfield University, Swindon, UK)				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army ARDEC Benet Laboratories, AMSTA-AR-CCB-O Watervliet, NY 12189-4050		8. PERFORMING ORGANIZATION REPORT NUMBER ARCCB-TR-02006		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army ARDEC Close Combat Armaments Center Picatinny Arsenal, NJ 07806-5000		10. SPONSORING / MONITORING AGENCY REPORT NUMBER		
11. SUPPLEMENTARY NOTES To be presented at the ASME Pressure Vessels and Piping Conference, Vancouver, Canada, 4-8 August 2002. To be published in proceedings of the conference.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.		12b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words) Yield pressure for a small permanent strain was measured in quasi-static laboratory tests of autofrettaged ASTM A723 steel cannon pressure vessels. Yield pressure was found to be a consistent ratio of the yield strength measured in close proximity to the area of observed yielding. Comparable yield pressure measurements for cannons firing with typical 5-ms pressure pulse duration gave 14% higher yield pressures, attributed to strain-rate effects on plastic deformation.  Calculated von Mises' yield pressure for the laboratory test conditions, including the Bauschinger-modified inner diameter residual stress and open-end vessel conditions, agreed with measured yield pressure within 3 to 5 %. Calculated yield pressure was found to be insensitive to the value of axial residual stress, since it is typically the intermediate value in the von Mises' yield criterion.  A description of yield pressure normalized by yield strength was given for autofrettaged A723 open-end pressure vessels over a range of wall ratio and degree of autofrettage, including effects of Bauschinger-modified residual stress. This method for calculating yield pressure is proposed as a design procedure for cannons and other pressure vessels.				
14. SUBJECT TERMS Yield Pressure, Cannons, Yield Strength, High-Strength Steels, Autofrettage, Bauschinger Effect		15. NUMBER OF PAGES 12		
		16. PRICE CODE		
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

## TABLE OF CONTENTS

	<u>Page</u>
ACKNOWLEDGEMENT .....	ii
INTRODUCTION.....	1
ANALYSIS .....	1
RESULTS FROM EXPERIMENT AND ANALYSIS .....	3
Measured Yield Pressure.....	3
Calculated Yield Pressure .....	5
Laboratory Versus Firing Pressurization .....	6
Effects on Calculated Yield Pressure .....	6
Yield Pressure Design .....	8
SUMMARY AND CLOSING .....	9
Closing Remarks .....	9
REFERENCES.....	10

### TABLES

1.	Yield Pressure Measurements and Analysis .....	5
2.	Material Strength and Degree of Autofrettage .....	5

### LIST OF ILLUSTRATIONS

1.	Pressure vessel configuration and some nomenclature .....	2
2.	Laboratory overpressure tests of A723 steel cannon tubes .....	4
3.	Laboratory and firing overpressure tests of A723 steel cannon tubes .....	4
4.	Effects of yield strength and longitudinal stress on yield pressure for cannon tubes .....	7
5.	Bauschinger and strength effects on calculated yield pressure of cannon tubes.....	7
6.	Yield pressure design curve for A723 steel pressure vessels with $S_Y =$ 1000 to 1200 MPa .....	8

## **ACKNOWLEDGEMENT**

The authors are pleased to acknowledge the help of Kenneth Olsen of Benet Laboratories who performed the laboratory tests described here.

## INTRODUCTION

Yielding of an autofrettaged thick cylinder, whether a cannon or some other type of pressure vessel, is a serious concern. Yielding of a vessel can affect function due to dimension change, it can decrease fatigue life due to loss of autofrettage residual stress, and yielding can be a safety hazard. Yield pressure is controlled by the applied and residual stresses in the vessel and by its material strength. The prudent user of a critical vessel should perform thorough stress analysis and material tests. However, accurate description of one control parameter for yielding of a thick cylinder—residual stress—can be elusive. Residual stress is difficult to measure, and calculated residual stresses can be affected by uncertainties in the analysis and input data, such as the nonideal Bauschinger yield properties of pressure vessel steels.

Recent work by Parker (ref 1) and Troiano et al. (ref 2) addresses some of the uncertainties of residual stress calculation for an autofrettaged cylinder. Methods have been developed that modify the familiar autofrettage residual stress distributions to account for Bauschinger-affected yield properties and the open-end loading condition that is appropriate for cannons and some other vessels. For the important inner diameter (ID) location of a vessel and for the ASTM A723 steel often used for high-pressure vessels, expressions are given (ref 2) for a useful range of diameter ratios and degree of autofrettage. These expressions are used here to calculate ID residual stress and the corresponding von Mises' yield pressure for comparison with measured yield pressure from cannon pressure vessels. Cannon sections with a range of yield strengths were quasi-statically pressurized in laboratory tests, and full-length cannons were pressurized by firing at a proving ground. Comparison of yield pressures from experiment and analysis will test the utility of Bauschinger-modified residual stress analysis for elastic strength design of pressure vessels.

## ANALYSIS

Early empirical results are still useful for estimating the strains at the ID of an autofrettaged cylinder, in order to determine the degree of autofrettage in the comparisons here. Davidson and Kendall (ref 3) provided an expression for the total strain,  $\epsilon_T$ , in the plastic region of an autofrettaged cylinder with inner, outer, and plastic radii,  $a$ ,  $b$ ,  $r_Y$ , respectively, as follows:

$$\epsilon_T E_M/S_Y = 1.08(1-2\nu)LN(a/r_Y) + [r_Y^2(1-\nu) - b^2(1-2\nu) + (r_Y^2 b^2/a^2)(2-\nu)]/[3b^4 + r_Y^4]^{1/2} \quad (1)$$

where  $E_M$  is elastic modulus (207,000 MPa),  $\nu$  is Poisson's ratio (0.3), and  $S_Y$  is yield strength of the cannons, listed in upcoming results. Figure 1 shows the configuration and some nomenclature. The approximate plastic radius for a given swage-autofrettaged cylinder can be determined by equating  $\epsilon_T$  with the interference strain,  $\epsilon_S$ , for a swage mandrel of radius,  $r_S$ , from the expression

$$\epsilon_S = (r_S - a)/a \quad (2)$$

Then the degree of autofrettage overstrain,  $n$ , is simply

$$n = (r_Y - a)/(b - a) \quad (3)$$

Equations (1) through (3) will be used to obtain the Bauschinger-modified hoop residual stresses at the tube ID for various values of  $n$ .

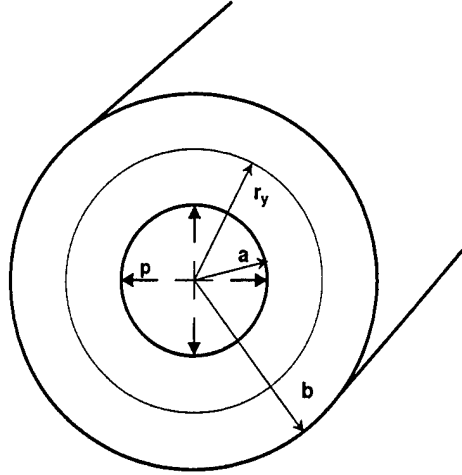


Figure 1. Pressure vessel configuration and some nomenclature.

The familiar Tresca plane-stress expressions for hoop residual stress in an autofrettaged tube were modified (refs 1,2) to apply to the von Mises' open-end conditions that are more appropriate for cannon pressure vessels and also to include the effect of the Bauschinger-reduced material compressive strength. The modified expressions for determining the hoop residual stress,  $S_{OE}$ , at the bore of an autofrettaged open-end tube of A723 steel are

$$S_{OE}/S_Y = \gamma R_S [(r_Y^2 - a^2) - 2b^2 \ln(r_Y/a)] / [b^2 - a^2] \quad (4)$$

where  $\gamma$  and  $R_S$  are the ratios that accomplish the modification for various tubes, and the remaining bracketed terms are the Tresca plane-stress expression for hoop residual stress. For A723 steel

$$\gamma = 1 / \{ [A(b/a) + B] \exp[ \{ C(b/a) + D \} \{ (r_Y/a) + E \} ] + [F(b/a) + G] \} \quad (5)$$

for  $r_Y/a > 1.5$ ;  $b/a > 1.75$

and  $R_S$  for all steels is

$$R_S = 1.669 - 0.165(b/a) - 0.730n^3 + 1.984n^2 - 1.887n \quad (6)$$

The constants in equation (5) for A723 steel are:

- $A = 0.0816$
- $B = -0.0562$
- $C = 1.7519$
- $D = -7.4597$
- $E = -1.315$
- $F = -0.1077$
- $G = 1.216$

Additional details and results for other steels are included in Reference 2.

Equations (4) through (6) are used here to calculate the hoop residual stresses at the ID of autofrettaged tubes, including the important effect of the Bauschinger-reduced strength for the type of steels used in cannons. Once the Bauschinger-modified hoop residual stresses are known, the Bauschinger-affected pressure,  $p_{VM}$ , at which the tube re-yields when subsequently pressurized can be determined, using the von Mises' criterion in the notation here

$$S_Y = [[(S_{\theta T} - p_{VM})^2 + (p_{VM} - S_{xR})^2 + (S_{xR} - S_{\theta T})^2]/2]^{1/2} \quad (7)$$

where  $S_{\theta T}$  is total hoop stress (sum of applied and residual) and  $S_{xR}$  is the axial residual stress. Effects of different formulations of axial residual stress on the resulting yield pressure are considered in upcoming results.

## RESULTS FROM EXPERIMENT AND ANALYSIS

### Measured Yield Pressure

Three breech-end sections of autofrettaged cannon tubes were used in laboratory tests in which pressure was applied in 15 MPa increments over the 600 to 850 MPa range. A press held the end load, creating open-end conditions. In separate tests, two cannons were fired with the firing pressure increased in similar increments over a similar range. In the laboratory tests, the permanent outer diameter (OD) hoop strain was measured at zero pressure after each increment. In the firing tests, the zero-pressure ID dimension was measured and the OD hoop strain was calculated from a correlation between OD strain and change in ID dimension established from laboratory tests. Plots of the OD strain for various applied pressures are shown in Figures 2 and 3. In all cases the permanent strain was measured in the chamber section of the cannon, with  $a = 79$ -mm and  $b = 148$ -mm. Following the pressurization tests, replicate hoop-orientation tensile tests were performed from material cut from the cannon chamber directly adjacent to the yielding location. The mean values of these yield strengths (0.2% offset), shown in Figures 2 and 3, give an accurate measure of material strength at the yielding location that is not affected by any variation of yield strength as a function of location in the cannon.



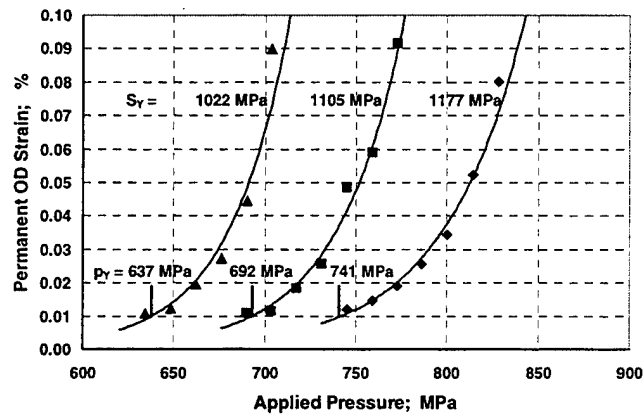


Figure 2. Laboratory overpressure tests of A723 steel cannon tubes;  $a = 79$ -mm,  $b = 148$ -mm.

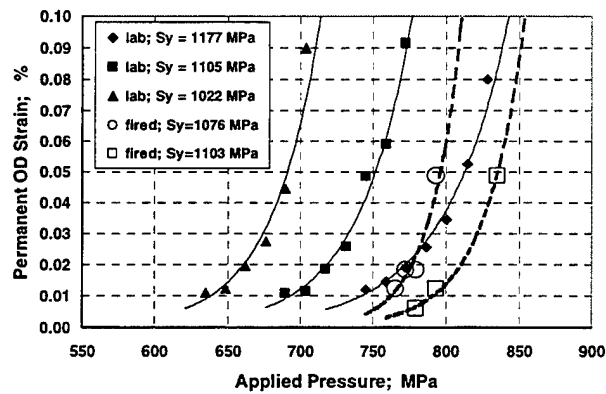


Figure 3. Laboratory and firing overpressure tests of A723 steel cannon tubes;  $a = 79$ -mm,  $b = 148$ -mm.

The laboratory OD strain versus pressure data shown in Figure 2 were fitted using an exponential expression from a spreadsheet in order to determine the pressure that produced 0.01% permanent OD hoop strain. This small value of OD strain corresponds to about one-third of the allowed variation in the OD dimension for a typical cannon tube. Values of this yield pressure at 0.01% strain, denoted  $p_Y$ , are listed in Figure 2 and Table 1 and compared with the yield strengths of the respective tubes. Note that  $p_Y$  is essentially constant with respect to material yield strength, as expected. This indicates that the overpressure and material strength tests were properly performed.

**Table 1. Yield Pressure Measurements and Analysis**

Strength $S_Y$ , MPa	Measured Yield Pressure		Calculated Yield Pressure	
	$p_Y$ , MPa	$p_Y/S_Y$	$p_{VM}$ , MPa	$p_Y/p_{VM}$
1022	637	0.62	622	1.03
1105	692	0.63	666	1.04
1177	741	0.63	705	1.05

**Calculated Yield Pressure**

The calculated yield pressures listed in Table 1 were determined as outlined in equations (1) through (7), with the following inputs and procedures:

- The  $a$  and  $b$  in equations (1) through (3) were the autofrettage dimensions, 57 and 157-mm, respectively.
- The  $r_S$  in equation (2) was 58.4-mm.
- The  $a$ ,  $b$ , and  $n$  in equations (4) through (6) were for the final chamber dimensions given earlier.
- The value assumed for the axial residual stress at the bore,  $S_{xR}$ , in equation (7) is zero.

The effect of other values of  $S_{xR}$  will be considered later. For these inputs, the calculated values of  $r_Y$  and  $n$  are listed in Table 2 for the laboratory tests and for two other arbitrary strength values (for later comparisons). The difference between  $n_{SWAGE}$  and  $n_{FINAL}$  is due to the difference between the autofrettage and final dimensions for the chamber region of the tube.

**Table 2. Material Strength and Degree of Autofrettage**

Yield Strength $S_Y$ , MPa	Yield Radius $r_Y$ , mm	Degree of Autofrettage	
		$n_{SWAGE}$	$n_{FINAL}$
Laboratory Tests:			
1022	140	0.82	0.88
1105	134	0.76	0.79
1177	129	0.72	0.73
Calculations:			
1250	125	0.68	0.67
1350	120	0.63	0.60

The calculated von Mises' yield pressures,  $p_{VM}$ , are listed in Table 1 and compared with the measured yield pressures. Note the 3 to 5% agreement between measured and calculated yield pressure, with the measured pressure slightly higher as expected, since it results from a permanent strain as discussed earlier. This close agreement supports the assumption that  $S_{xR} = 0$  in equation (7) is a reasonable choice for an open-end cannon pressure vessel.

### Laboratory Versus Firing Pressurization

Comparison of overpressure test results under quasi-static laboratory and rapid loading firing conditions is shown in Figure 3. The laboratory results are the same as those in Figure 2, with total rise time from zero to peak pressure of about 10 seconds. The firing tests had a rise time of about 5 milliseconds, more than  $10^3$  faster, which raises the concern of time rate effects on the overpressure results. The yield strengths shown for the two fired tubes were determined as discussed earlier, with replicate tests taken directly from the location of observed yielding. Thus, the significantly higher pressure required for yielding of the fired tubes is attributed to time rate effects. Note particularly the pressure at 0.01% OD strain for the fired tube with  $S_Y = 1103$  MPa, about 790 MPa, compared with the corresponding pressure for the laboratory tube with  $S_Y = 1105$ , about 690 MPa. This 14% higher yield pressure for the fired tube is attributed mainly to strain-rate effects causing delayed plastic deformation, rather than to an increase in yield strength. Kendall and Davidson (ref 4) measured about 3% increase in yield strength for a  $10^3$  increase in strain rate for a similar steel, whereas Dowling (ref 5) discusses 10% increases in ultimate tensile strength for metals due to delayed plastic creep for a  $10^3$  increase in rate. Thus, the increase in the effective yield pressure of a fired cannon is attributed primarily to delayed plastic deformation at the firing strain rate.

### Effects on Calculated Yield Pressure

The importance of key inputs to calculated yield pressure of an autofrettaged thick cylinder is considered in the results of Figures 4 and 5. Figure 4 shows the results of different assumptions for values of the axial stress at the tube ID. The von Mises' yield pressure was calculated as described earlier, except using two alternative expressions for axial stress, in addition to the usual plane-stress open-end condition of  $S_{R-x} = 0$ . The other two are

$$S_{R-x} = \nu S_{R-\theta} \quad (10)$$

equating the axial residual stress to a (Poisson's ratio) portion of the hoop residual stress, as described by Parker (ref 1), and

$$S_x = S_{MAX} = pr_p^2 / (b^2 - a^2) \quad (11)$$

where  $S_x$  is the maximum transient applied axial stress that can exist in a fired tube when a rapidly applied pressure,  $p$ , acts on the closed breech end of the tube with a radius  $r_p$ . Although it is unclear whether the 5-ms duration of firing pressure can produce enough transient axial stress to affect yielding, this upper-bound estimate of axial stress may have some utility.

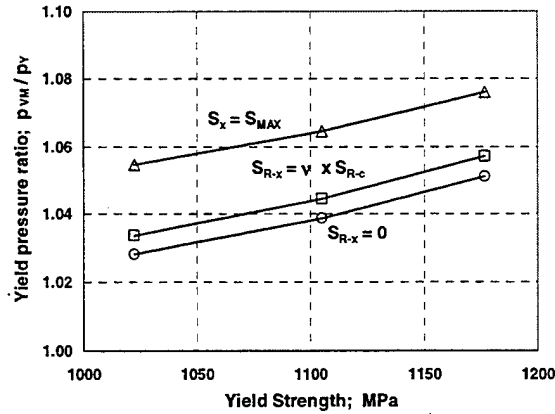


Figure 4. Effects of yield strength and longitudinal stress on yield pressure for cannon tubes;  $a = 79$ -mm,  $b = 148$ -mm.

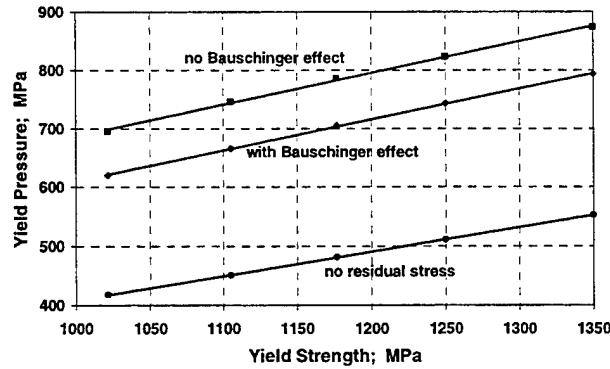


Figure 5. Bauschinger and strength effects on calculated yield pressure of cannon tubes;  $a = 79$ -mm,  $b = 148$ -mm.

The calculated yield pressure results for  $S_{R-x} = 0$  in Figure 4, normalized by measured yield pressure, show the 3 to 5% agreement discussed earlier. For the  $S_{R-x} = \nu S_{R-\theta}$  assumption, the result changes little, with 3 to 6% agreement between calculated and measured yield pressure. This can be explained by the fact that the axial stress is intermediate in value of the three stresses in the Mises' criterion and thus would be expected to have little effect on yielding. The yield pressure calculated from the upper-bound estimate of  $S_x$  can be seen to be 5 to 8% above the measured yield pressure. Considering this small effect and its low likelihood of occurrence and only for rapidly applied pressurization, it will be considered no further. All upcoming calculations of yield pressure will be for  $S_{R-x} = 0$ .

Figure 5 summarizes the important effects of autofrettage hoop residual stress on yield pressure, including the cases of no residual stress ( $S_{OE} = 0$ ), residual stress with no Bauschinger effect ( $\gamma R_S = 1$ ), and residual stress with Bauschinger effect (equations (1) through (7) as written). As expected, yield pressure with Bauschinger modified residual stress described here is considerably higher, by 44 to 49%, compared to that with no hoop residual stress. If hoop residual stress were used with no Bauschinger modification, still higher yield pressure would be

predicted, 10 to 12% above that with Bauschinger modification. However, use of yield pressure calculated with no Bauschinger modification is unwise. It appears that the nonideal, reduced compressive strength properties referred to as the Bauschinger effect are inevitably present in autofrettaged thick cylinders.

### Yield Pressure Design

A review of equations (4) through (7) shows that a dimensionless ratio of yield pressure divided by material yield strength can be calculated as a function of two dimensionless variables, the wall ratio of the cylinder,  $b/a$ , and the degree of autofrettage,  $n = (r_Y - a)/(b - a)$ . Plots of this type would be useful for design, particularly so since they would include the important Bauschinger-modified ID hoop residual stress from recent work (refs 1,2). Figure 6 is such a plot, calculated as has been described and also including the measured yield pressures and yield strengths from the laboratory overpressure tests.

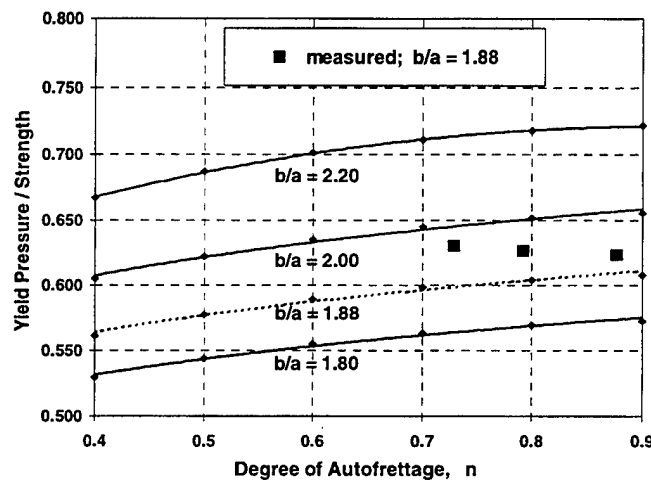


Figure 6. Yield pressure design curve for A723 steel pressure vessels with  $S_Y = 1000$  to  $1200$  MPa.

First, note the diminishing return in yield pressure with increasing values of both  $n$  and  $b/a$ . For a series of equal increases in  $n$  or  $b/a$ , the corresponding increase in normalized yield pressure becomes progressively smaller. This has yield pressure design implications. Second, note that calculations were performed for  $b/a = 1.88$ , corresponding to the wall ratio of the laboratory tests. The measured  $p_Y$  and  $S_Y$  and the  $n$  for the laboratory tests (from Tables 1 and 2) were used to provide the direct comparison between measured and calculated yield pressure shown in the plot. The 3 to 5% agreement discussed earlier can be seen. It is proposed that the results of Figure 6 can be used for Bauschinger-modified yield pressure design of autofrettaged, thick, open-end cylinders made from A723 pressure vessel steel in the material strength range considered here, 1000 to 1200 MPa. Now that Bauschinger material property data are available for other steels used for pressure vessels (ref 2), the same type of yield pressure design information can be made available for these steels.

## SUMMARY AND CLOSING

Measured yield pressure for a small permanent OD strain (0.01%) from quasi-static laboratory pressurization of autofrettaged A723 steel cannon pressure vessels was found to be a consistent ratio of yield strength measured at the yield location. Comparable yield pressure measurements, except for the rapid loading (5-ms pressure pulse) of cannon firing, gave 14% higher yield pressures, attributed to strain-rate effects delaying the plastic deformation.

Calculated von Mises' yield pressure for the laboratory test conditions and including Bauschinger-modified ID residual stress and open-end vessel conditions showed agreement with measured yield pressure within 3 to 5%. Calculated yield pressure was found to be insensitive to the value of axial residual stress, which has an intermediate value in the von Mises' yield criterion.

A general description of Bauschinger-modified yield pressure normalized by yield strength was given for autofrettaged A723 open-end pressure vessels over a range of wall ratios and degree of autofrettage. The calculated yield pressures are shown to agree well with the quasi-static yield pressure measurements from this work. This method for calculating yield pressure is proposed as a design procedure for cannons and other pressure vessels.

### Closing Remarks

Two fundamental assumptions are implicit in the model calculations described here. Firstly that, when an autofrettaged cylinder is repressurized, the material behaves in an ideal linear-elastic, perfectly plastic fashion and secondly that the onset of further plasticity so predicted is associated with additional permanent plastic strain near the bore following depressurization. Given the convincing agreement with experimental evidence, these are likely subtle and second-order concerns. Nevertheless future work should include a more detailed numerical assessment of such potential interactions.

## REFERENCES

1. Parker, A. P., "Autofrettage of Open End Tubes – Pressures, Stresses, Strains and Code Comparisons," *Journal of Pressure Vessel Technology*, Vol. 123, 2001, pp. 271-281.
2. Troiano, E., Parker, A.P., Underwood, J.H., and Mossey, C., "Experimental Data, Numerical Fit, and Fatigue Life Calculations Relating to the Bauschinger Effect in High Strength Armament Steels," *Proceedings of Guns and Pressure Vessels: Design, Mechanics and Materials*, 15-18 September 2002, Oxford, UK.
3. Davidson, T.E., and Kendall, D.P., "Design of High Pressure Containers," *Mechanical Behavior of Metals Under Pressure*, (H. Pugh, ed.), Elsevier, 1970, pp. 54-77.
4. Kendall, D.P., and Davidson, T.E., "The Effect of Strain Rate on Yielding in High Strength Steels," *Journal of Basic Engineering*, Vol. 88, Series D, No. 1, 1966, pp. 37-44.
5. Dowling, N.E., *Mechanical Behavior of Materials*, Prentice Hall, 1999, pp. 123-5.

---

TECHNICAL REPORT INTERNAL DISTRIBUTION LIST

	<u>NO. OF COPIES</u>
TECHNICAL LIBRARY ATTN: AMSTA-AR-CCB-O	5
TECHNICAL PUBLICATIONS & EDITING SECTION ATTN: AMSTA-AR-CCB-O	3
OPERATIONS DIRECTORATE ATTN: SIOWV-ODP-P	1
DIRECTOR, PROCUREMENT & CONTRACTING DIRECTORATE ATTN: SIOWV-PP	1
DIRECTOR, PRODUCT ASSURANCE & TEST DIRECTORATE ATTN: SIOWV-QA	1

NOTE: PLEASE NOTIFY DIRECTOR, BENÉT LABORATORIES, ATTN: AMSTA-AR-CCB-O OF ADDRESS CHANGES.

---



---

TECHNICAL REPORT EXTERNAL DISTRIBUTION LIST

	<u>NO. OF COPIES</u>		<u>NO. OF COPIES</u>
DEFENSE TECHNICAL INFO CENTER		COMMANDER	
ATTN: DTIC-OCA (ACQUISITIONS)	2	ROCK ISLAND ARSENAL	
8725 JOHN J. KINGMAN ROAD		ATTN: SIORI-SEM-L	1
STE 0944		ROCK ISLAND, IL 61299-5001	
FT. BELVOIR, VA 22060-6218			
COMMANDER		COMMANDER	
U.S. ARMY ARDEC		U.S. ARMY TANK-AUTMV R&D COMMAND	
ATTN: AMSTA-AR-WEE, BLDG. 3022	1	ATTN: AMSTA-DDL (TECH LIBRARY)	1
AMSTA-AR-AET-O, BLDG. 183	1	WARREN, MI 48397-5000	
AMSTA-AR-FSA, BLDG. 61	1	COMMANDER	
AMSTA-AR-FSX	1	U.S. MILITARY ACADEMY	
AMSTA-AR-FSA-M, BLDG. 61 SO	1	ATTN: DEPT OF CIVIL & MECH ENGR	1
AMSTA-AR-WEL-TL, BLDG. 59	2	WEST POINT, NY 10966-1792	
PICATINNY ARSENAL, NJ 07806-5000			
DIRECTOR		U.S. ARMY AVIATION AND MISSILE COM	
U.S. ARMY RESEARCH LABORATORY		REDSTONE SCIENTIFIC INFO CENTER	2
ATTN: AMSRL-DD-T, BLDG. 305	1	ATTN: AMSAM-RD-OB-R (DOCUMENTS)	
ABERDEEN PROVING GROUND, MD		REDSTONE ARSENAL, AL 35898-5000	
21005-5066			
DIRECTOR		COMMANDER	
U.S. ARMY RESEARCH LABORATORY		U.S. ARMY FOREIGN SCI & TECH CENTER	
ATTN: AMSRL-WM-MB (DR. B. BURNS)	1	ATTN: DRXST-SD	1
ABERDEEN PROVING GROUND, MD		220 7TH STREET, N.E.	
21005-5066		CHARLOTTESVILLE, VA 22901	
COMMANDER			
U.S. ARMY RESEARCH OFFICE			
ATTN: TECHNICAL LIBRARIAN	1		
P.O. BOX 12211			
4300 S. MIAMI BOULEVARD			
RESEARCH TRIANGLE PARK, NC 27709-2211			

---

NOTE: PLEASE NOTIFY COMMANDER, ARMAMENT RESEARCH, DEVELOPMENT, AND ENGINEERING CENTER,  
 BENÉT LABORATORIES, CCAC, U.S. ARMY TANK-AUTOMOTIVE AND ARMAMENTS COMMAND,  
 AMSTA-AR-CCB-O, WATERVLIET, NY 12189-4050 OF ADDRESS CHANGES.

---